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Invited Review Article: Strategies and Processes for High Quality Wire Arc Additive Manufacturing

27 June 2018

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Abstract

Wire Arc Additive Manufacturing (WAAM) is attracting significant attention in industry and academia due to its ability to capture the benefits of additive manufacturing for production of large components of medium geometric complexity. Uniquely, WAAM combines the use of wire and electric arc as a fusion source to build components in a layer-by-layer approach, both of which can offer significant cost savings compared to powder and alternative fusion sources, such as laser and electron beam, respectively. Meanwhile, a high deposition rate, key for producing such components, is provided, whilst also allowing significant material savings compared to conventional manufacturing processes. However, high quality production in a wide range of materials is limited by the elevated levels of heat input which causes a number of materials processing challenges in WAAM. The materials processing challenges are fully identified in this paper to include the development of high residual stresses, undesirable microstructures, and solute segregation and phase transformations at solidification. The thermal profile during the build poses another challenge leading to heterogeneous and anisotropic material properties. This paper outlines how the materials processing challenges may be addressed in WAAM by implementation of quality improving ancillary processes. The primary WAAM process selections and ancillary processes are classified by the authors and a comprehensive review of their application conducted. Strategies by which the ancillary processes can enhance the quality of WAAM parts are presented. The efficacy and suitability of these strategies for versatile and cost effective WAAM production are discussed and a future vision of WAAM process developments provided.

Keywords: Additive Manufacturing, Wire Arc Additive Manufacturing, Processes

1. Introduction

In recent years, Directed Energy Deposition (DED) techniques have enabled cost effective additive manufacturing of large, medium complexity metallic components. The effectiveness of DED in manufacturing these part types can be attributed to unconstrained build volumes and substantially higher deposition rates than alternative approaches such as Powder Bed Fusion. The lower resolution and need for post finish machining in DED is readily offset by the enhanced processing efficiency. Meanwhile significant raw material savings are possible in comparison to conventional approaches such as CNC machining and forging [1].They do not require specific tooling, as in casting and forging, therefore, manufacturing costs are significantly lower specifically for low production volumes and significant reduction in cycle time can be expected [2]. Complementary to this, is the ability to use wire as feedstock in DED, which offers high efficiency material deposition eliminating the need for peripheral powder recycling processes [3], reducing health and safety concerns and offering a significant reduction in price per kilogram compared to powder in a range of engineering materials including aerospace alloy Ti-6Al-4V [4], stainless steel and nickel based superalloys as shown in table 1.

Table 1 Approximate cost per kilogram in wire and powder compiled from supplier quotes sourced in 2016.

Feedstock	Cost per kilogram (£/kg)			
	Ti-6Al-4V	Inconel 718	Inconel 625	Stainless Steel 316L
Wire	120	58	49	12
Powder	280	80	80	40

Wire arc additive manufacturing (WAAM) is a wire-based DED approach that uses an electrical arc as a source of fusion to melt the wire feedstock and deposit a part preform, layer by layer. Use of an electrical arc as a fusion source provides a number of processing advantages, compared to electron beam and laser which are the alternative sources of fusion in DED outlined in the “Standard Guide for DED of Metals,” part of the ASTM F3187 - 16 standard series [5]. A major benefit of the WAAM process relates to the low capital investment, as the components of a WAAM machine may be derived of open source equipment, sourced from an array of suppliers in the mature welding industry [6]. The processing characteristics may also make the WAAM process preferable compared to the alternative fusion sources. For example, WAAM does not does not need a vacuum environment to operate as required in electron beam based methods [7]. As such, prolonged set up and ramp down times which can lead to over-aging in precipitate hardened materials can be avoided [8]. Whilst inert shielding gas may not be required in electron beam DED to avoid atmospheric contamination, there is an elevated susceptibility to element depletion and evaporation during processing [9]. In comparison to laser based methods, the use of the electrical arc offers a higher efficiency fusion source [10]. This is of benefit from an energy consumption perspective, in particular, for reflective metal alloys of poor laser coupling efficiency such as aluminium, copper [11] and magnesium [12]. With typical layer heights of 1-2mm, surface waviness of 500µm [13] and deposition rates up to 10kg/hr, WAAM productivity and material removed is similar to laser-based and electron beam-based DED approaches.

Research and developments have allowed the WAAM process to become highly capable in a number of materials, including aerospace titanium alloy Ti-6Al-4V [14] and nickel bronze [15], where static mechanical properties close to those found in wrought and cast can be produced [16]. As shown in table 2, at present there are several commercial WAAM machine manufacturers and/or service providers able to produce WAAM components in a number of materials. However, high quality production of WAAM parts is only achievable when the specific materials processing challenges related to the high-levels of heat input of the WAAM process are addressed.

Table 2 Commercial WAAM DED technologies categorised by energy source and feedstock

Commercial WAAM machine manufacturers and/or service providers	Deposited Material
Norsk Titanium AS [17]	Ti6Al4V
Gefertec [18]	Inconel 718, 625, Ti6Al4V, invar and range of mild steels, stainless steels & aluminium alloys.
Prodways [19]	Ti6Al4V
Mazak [20]	Not specified
Glenalmond Technologies [21]	Not specified

Williams, et al. [13] and Ding et al. [22] regarded the management of the high levels of residual stress and distortion as the primary heat-related material processing challenge in WAAM. Ding et al. [22] considered the surface finish of WAAM parts another major concern to dimensional compliance as well as premature part failure. Practical methods of mitigating these issues were presented, but were limited in scope primarily to build strategies for the management of residual stress. Pan et al. [16] summarised of static mechanical properties achieved in WAAM research, reporting the welding technology and processing condition, e.g. heat treated, interlayer cooling etc. however, the mechanisms of material property improvements were not discussed. This paper identifies the full range of materials processing challenges in WAAM. The primary process selections and ancillary processes that may be used in WAAM are classified by the authors and the strategies in which they may be deployed to overcome these challenges are presented. Finally, future challenges and opportunities in the area of WAAM are identified.

2. Materials processing challenges in WAAM

The materials processing challenges in WAAM relate to the achievement of the performance measures related to geometric, physical and material properties as shown in figure 1 with several examples of possible requirements presented. The deposition rate of the process is essential to commercial adoption of WAAM as a high deposition rate DED process. This consequently comprises the final performance measure, which the aforementioned performance measures must be sustained relative to. Depending on material and the application, typical deposition rates for WAAM are reported in region of 1-10kg/hr.

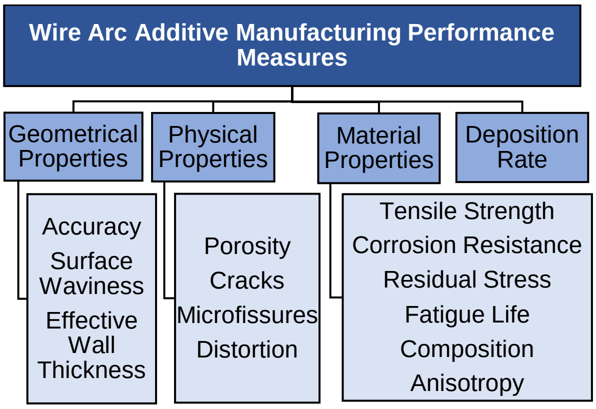

Figure 1 Performance measures in WAAM

In WAAM, solidification presents a major materials processing challenge due to the promotion of a microstructure containing large columnar grains. Although this is beneficial for applications requiring high temperature creep resistance [23], at regular operating temperatures it provides lower strength, toughness and corrosion resistance compared to a fine equiaxed microstructure [24]. A fine equiaxed microstructure tends to be difficult to develop in WAAM and other additive manufacturing technologies, as beyond an epitaxial growth zone close to the substrate, grains tend to grow in a competitive grain growth process in which the total number of grains reduce leading to grain enlargement [25]. The most dominant grain growth occurs in the preferred crystallographic orientations that correspond with the maximum thermal gradient. Due to the relatively low energy density of the electrical arc which results in low thermal gradient and low solidification rate [26], the heat sink effect of the substrate [27] can result in pronounced columnar grain growth aligned transverse to the weld direction as shown in figure 2 [28]. This grain growth can progress without interruption due to minimal grain nucleation mechanisms in WAAM, and consequently provides conditions for development of substandard and anisotropic mechanical properties which occur as shown in table 3.

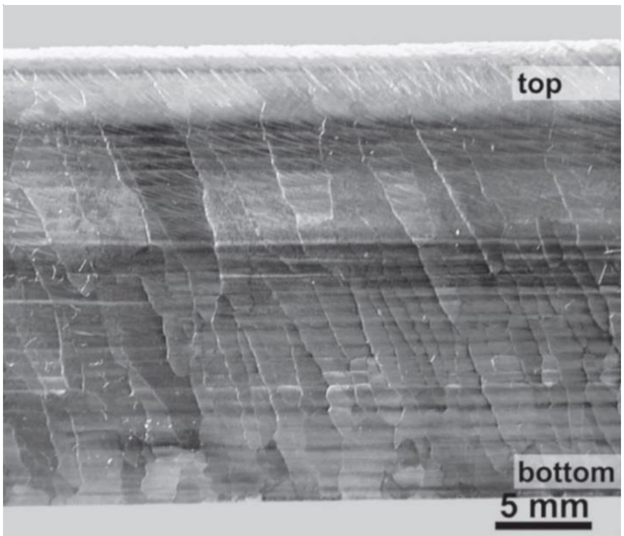

Figure 2 Large columnar WAAM grain growth shown in Ti-6Al-4V [28]

Table 3 WAAM mechanical properties reported in the literature compared to industrial standards

Material and direction	Process	0.2% YS (MPa)	UTS (MPa)	Elong. (%)	Ref.
Ti-6Al-4V	Wrought	≥830	≥900	≥10	[29]
(X-Y)	As deposited	870±30	920±20	12±5	
(X-Y)	Rolled	1030±5	1080±15	13±1.5	[14]
(Z)	Rolled	990±30	1080±5	13±1	
(X-Y)	As deposited	868	971	8.6	[27]
(Z)	As deposited	803	918	14.5	
Inconel 718	Wrought	≥1034	≥1276	≥12	[30]
(X-Y)	As deposited	473 ± 6	828 ± 8	28±2	[31]
Aluminium 2219	*(T851)*	≥317	≥427	≥8	[32]
(X-Y)	As deposited	114±4.8	263±0.5	18±0.5	[33]
(Z)	As deposited	106±0.8	258±2.2	15.5±1	
(X-Y)	Special HT	269±28,	418±22	10.24	[34]
(Z)	Special HT	254±28	365±28	7.44	

There is a lack of driving force in the solidified WAAM deposit for the recrystallisation to occur in order to generate new refined grains, whilst detrimental grain coarsening remains possible [35]. This is an issue in materials that do not undergo solid state phase transformations such as ferritic and austenitic stainless steels as post-build heat treatments cannot be used to grain refine [36]. Even in heat-treatable materials, the initial morphology can even persist through phase transformations, as demonstrated in WAAM of Ti-6Al-4V, where the strong fibre texture of the large primary β grains decomposes to a similarly undesirable α texture [37]. Furthermore, whilst precipitation hardened materials may be solutionised and aged in a post build heat treatment process to develop the desired microstructure, processing issues may be incurred during the WAAM process, due to the large grain growth and solute segregation leading to defective parts.

Solidification cracking is promoted by excessive solute segregation, in the presence of high levels of residual stresses and enlarged grain size [38, 39], both of which are common in WAAM. The crack resistance is particularly poor in materials with high coefficient of thermal expansion and extensive solute segregation, such as heat treatable aluminium alloys and materials where crystal structure is easily degraded due to the heat induced grain coarsening, such as in ferritic stainless steels [40]. The significant residual stress [41] can result in significant distortion as shown in figure 3 [42] leading to build failure and reduced fatigue life [43], and stress corrosion resistance [44]. The solute distribution at solidification, also influences the phase transformation regardless of cooling rate [45]. This may prevent formation of solid state strengthening precipitates in a fine dispersed manner as shown in the WAAM production of the aluminium alloy 2219 [46]. Sensitization involving carbide precipitation is also possible welding in austenitic stainless steels of non-stablised composition [47] leading to loss of intergranular corrosion resistance [48]. The thermal profile in WAAM causes the deleterious Inconel 718 [31] and Inconel 625 [49] causes the deleterious Laves phase to develop. This phase consumes local niobium concentrations which prevents effective formation of the gamma prime strengthening phase and causes embrittlement of the deposit [50].

Figure 3 Structural distortion of a WAAM part due to residual stress [42]

Variations in thermal profile locally or differences in thermal histories, present a material processing challenge as these can cause different phases and microstructures to develop within the build, leading to inhomogeneous material properties. Evaporation of low melting point elements and adsorption of atmospheric gases due to heat dependency, can progressively occur affecting composition and oxidation of WAAM parts [51]. Variations in thermal profile occur when the heat flux changes from steady state due to change in heat dissipation due the geometry, or a varying numbers thermal cycles are experienced. In the change of local geometry between substrate to thin wall, the heat transfer mode transitions from mainly conduction-based heat dissipation near the substrate as shown in figure 4a, to include a greater proportion of radiation and convection within the thin wall section as shown in figure 4b. As the heat dissipation becomes less effective and pre-heat from the previous layer is introduced, heat can accumulate along the build direction [52] leading to a transition zone of microstructural and dimensional variation which in some cases complete loss of weld bead dimensional control [53]. Variation in wear rate performance along the build direction was also found in mild steel ER70S and stainless steel 304 [54]. Furthermore, the extent of thermal cycling affects the macroscale properties of the part. This leads to local variations in material properties as evident through the different microstructures shown in the top layers in contrast to the middle layers for WAAM deposits in Ti-6Al-4V [55], maraging steel [56] and Al-6.3%Cu [57].

To minimise the effect of heat accumulation, an interlayer dwell period is commonly used, based on a fixed time interval or a time linked to reaching a fixed interpass temperature [58]. If these values are specified such that deposition is carried out on a surface of low enough temperature, steady state deposition is possible, identifiable by a constant weld pool size. However, determination of a suitable interpass temperature tends to be by resource intensive trial and error, with limited systematic approaches proposed [59]. Additionally, the interpass temperature is difficult to control, and has been shown to easily lead to temperature variations up to 100K [60]. The effectiveness is also limited to sections of consistent heat dissipation limiting the applicability for commercial parts. With the inclusion of adjacent weld beads in multi-layer deposition, as shown in figure 4c, the heat transfer characteristic becomes more variable in the build direction, providing less opportunity for steady state deposition to develop. Thermal cycling effects also becomes more complex due to deposition of adjacent in addition to vertical weld beads.

For WAAM builds with variation in bulk cross sectional areas inherent to the design, or feature addition remanufacturing and repair applications [2], the achievement of homogenous and satisfactory material properties will be particularly challenging, especially properties presented to date in the WAAM literature consist of material properties sourced from samples in which steady state deposition has been achieved (excluding transition zone regions). An alternative approach to minimising the effect of heat accumulation involves the progressive reduction of the heat input from the welding torch [61]. However, as in the case of introducing an interlayer dwell period, this approach can reduce productivity due to reduction in wire feed speed [62]. The heat dissipation and the impact of thermal cycles may also be affected through the infill strategy employed. In woven path strategy, the amplitude and frequency is important in the development of the peak temperature and average temperature in the weld bead [63]. The Welding Institute [64] note that the woven weld path resulted in different mechanical properties of a deposit compared to parallel approach, whilst also reducing inhomogeneities due to start and stops. Whilst, these results indicate that the deposition pattern, direction and route made by the welding torch strongly affect the heat transfer characteristic and the thermal cycles, to date it is not clear if path planning approaches alone are able to overcome the issue of heterogeneity in WAAM parts.

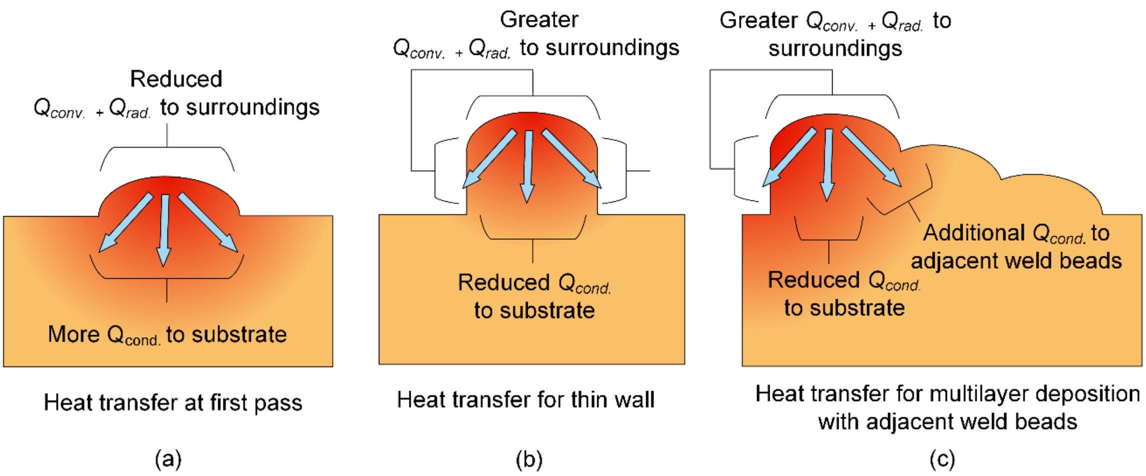

Figure 4 Schematic diagram of the heat dissipation modes, conduction (Qcond), convection (Qconv), radiation (Qrad), (a) at the beginning of WAAM (b) during the build of a thin wall part and (c) for a part with overlapping weld beads

3. Classification of primary process selections in WAAM

To establish the capability of WAAM for producing parts of a particular material, the material characterisation is required. Primary process selections at this stage include the welding technology, welding process parameters, shield gas, wire, substrate, and motion system as outlined in figure 5.

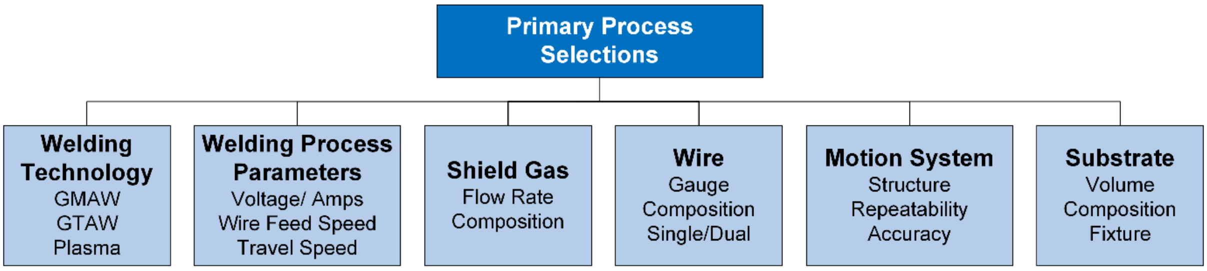

Figure 5 Primary process selections to perform materials characterisation in WAAM

The welding technology that may be employed in WAAM include Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW) or Plasma Arc Welding (PAW). Each category and the variants within have been detailed by Pan, et al. [16]. Selection of welding technology is driven by the user application. For example, if high deposition rate is prioritised, GMAW may be preferred to GTAW, although quality and process stability is generally lower [25]. Although PAW, provides the highest energy density electrical arc that enables high travel speeds and high-quality welds of minimised distortion, it typically requires the most extensive capital expenditure [65].

Material considerations may also drive the welding technology selection, for example to obtain cathodic cleaning action to remove the oxide surface layer in welding aluminium alloys. Another consideration is the prevention of arc wander with titanium alloys [66] which eliminates GMAW as a solution in this material. As wire feed is only coaxial through the weld torch in GMAW, the PAW, and GTAW approaches require a method to re-orientate the wire and the deposition direction changes to achieve consistent metal transfer. However, Wu et al. [67] showed that geometrically consistent deposition could be achieved for any travel direction with a wire feed angle set up of 60° offering a possible solution to this issue. Geng, et al. [68] also developed a mathematical model to ensure that wire offset could be updated with change in angle to achieve consistent deposition.

The welding parameters, including nominal current, wire feed speed (WFS) and travel speed (TS) are instrumental to the thermal profile in WAAM and thus the material properties, dimensional stability and wettability of substrate [69]. The heat input is determined by the following equation:

$$Heat\ input = \frac{Voltage\ x\ current}{Travel\ speed} \quad (1)$$

A limited range of process parameter combinations result in a defect free, stable weld bead deposit and this region can be represented within a process map. Lower heat input processes may also act to reduce porosity content due to the reduction in droplet temperature as well as gas solubility in the weld pool [70].   A constant specific heat input is represented by WFS/TS ratio and is one way to ensure adjustments of the process parameters will also result in stable deposition. Williams, et al. [13] found that a WFS/TS ratio of 30 effectively resulted in stable deposition for PAW-based WAAM of Ti6Al4V. Many welding power supplies include synergic welding programs to ensure welding processes are stable for a given material. However, these have been designed for single pass welding processes i.e cool substrate, synergic programs may not remain suitable if heat accumulates during a WAAM build. Due to the narrow processing window in WAAM, there is subsequently limited ability to control the heat dissipation characteristic in to transfer across solidification modes and to modify the microstructure as seen in electron beam additive manufacturing [71].

An adequate flow rate of shield gas is required to flood the area surrounding hot weld metal in WAAM to exclude atmospheric gases and prevents the formation of detrimental oxides, nitrides and porosity [66]. Too high a flow rate can result in poor penetration and porosity can be introduced due to turbulence drawing in atmospheric gases to the gas column. In most cases, the shield gas is delivered through the welding torch, however, for materials that are highly susceptible to atmospheric contamination such as Ti-6Al-4V and maraging steel as shown in figure 6 [56], additional measures may be required. This includes the use of inert chambers or flexible tents, however these have prolonged purge times. Ding, et al. [72] developed a local shielding device for WAAM builds of Ti-6Al-4V. By providing laminar flow of shield gas, as opposed to conventional local shielding devices, the protection zone could be extended to the side walls during the build of WAAM components.

Figure 6 WAAM walls of maraging steel showing degradation with oxide accumulation for torch only shielding [73]

The composition of the shield gas is important due to the influence on the heat transfer in the welding zone [74]. Argon is commonly used and additions of elements of higher dissociation and ionization potential than argon, such as active gases such as carbon dioxide, or helium, nitrogen and hydrogen [75] offer the ability to able to raise the temperature of the arc [76]. Sequeira Almeida and Williams [77] were able to produce Ti-6Al-4V samples with refined prior β grains due to enhanced cooling rate provided by using argon shielding gas mixture with higher helium content.

The process selections regarding the wire in WAAM are instrumental to the performance measures. The wire gauge and the number of wires fed into the arc for given welding process parameters affect the deposition rate, the heat transfer within the weld pool, imparting a chilling effect as mass is increased [78]. This can lead to lack of fusion defects without careful optimisation of the welding processing parameters. It has been shown possible to use multiple wires for in-situ alloying. This is useful for materials of compositions that are difficult to obtain in singular wire form such as γ- titanium aluminide [79] and iron aluminide [80]. The presence of diameter variations, cracks or scratches on the wire surface can lead directly to porosity within the deposited material [81]. Murav'ev, et al. [82] found higher quality wire greatly reduced porosity in the welded joint in welding of titanium alloys.

A further effect of the wire process selections is related to composition of the wire and content of inoculants. Inoculants can act as heterogeneous nuclei, increasing the number of locations from which grains can develop. However, they can also act to increase the level of constitutional supercooling by the compositional change involved. This lowers the temperature in the solidifying mushy zone to below the equilibrium solidus temperature of the metal alloy which increases the tendency for grains to solidify. Bermingham, et al. [83] effectively demonstrated inoculation by modifying Ti-6Al-4V with trace boron additives. This promoted thinner β-grains in WAAM a more equiaxed dendritic structure developed. Mereddy, et al. [84] investigated the addition of silicon to commercially pure titanium and found that grain refinement was achieved, although it was eliminated due to thermal reheating cycles which caused grain growth. Elements with a strong affinity to oxygen such as silicon, can also form oxides, which act to pin the grain boundaries and limit grain growth in stainless steel [85]. Haselhuhn investigated compositional change in 4047 and 4943-based aluminium alloys with additions of magnesium, strontium, titanium boride, and combinations, with combination of strontium and titanium boride in the high-silicon producing the finest eutectic structure in the study [86].

The composition of the substrate is important due to wettability of the weld bead to the surface which may be difficult in dissimilar materials. Dilution of the first layer of deposit must also be considered. The thickness and stiffness of the substrate provides resistance to distortion. Mechanical tensioning of the workpiece through heavy jigs, fixings, clamps and other technologies, can also restrict the possible distortion, however may increase the formation of residual stresses. [87]. While these mechanical adjustments might prove effective, they require extra financial resources and can restrict the flexibility of changes regarding the product geometry.

Cartesian (linear XYZ), 5 Axis, articulated robotic arm and parallel kinematic machines have been investigated for use to provide the necessary relative motion between the weld-torch and build plate. Due to the importance of the arc length and the relative position of the wire on heat input and weld bead dynamics [69], the positional repeatability and accuracy affects the geometrical, physical, and material properties of the weld. If the motion system is less accurate, a greater volume of material may be required to be removed in post-processing, detrimentally affecting the cost effectiveness of WAAM. Cartesian systems are typically more stiff and accurate than articulated robotic arm systems [88]. Robotic systems are also more prone to speed reduction at sharp corners which can result in systematic humping of material [89]. However, articulated robotic systems are more practical for very large build volumes due to their maneuverability and optional parallel working. In addition, despite low accuracy, high repeatability can be achieved. Retrofitting to WAAM capability to CNC machines, has been implemented by several investigators [90] [91] and is reported to be a cost effective approach to WAAM [92] providing the ability to deposit and finish machine in the same set up in a hybrid process.

4. Classification of ancillary processes in WAAM

Ancillary processes are increasingly implemented in WAAM to improve the material performance measures that are achievable with primary process selections. The ancillary WAAM processes are classified by the authors as shown in figure 7, by timing of application relative to the deposition process and by the overarching process mechanism. The latter relate to modifying the thermal profile relative to common point in space and successive layer completions respectively and their operation is therefore decoupled from the WAAM deposition [93]. Although post build strategies are commonly used, these form costly and often time consuming aspects of the process chain. Furthermore as outlined in section 2, these approaches are often unsuccessful in addressing the heat based materials processing challenges in WAAM. The following sections consequently review the capability in-situ and inter/intralayer ancillary processes.

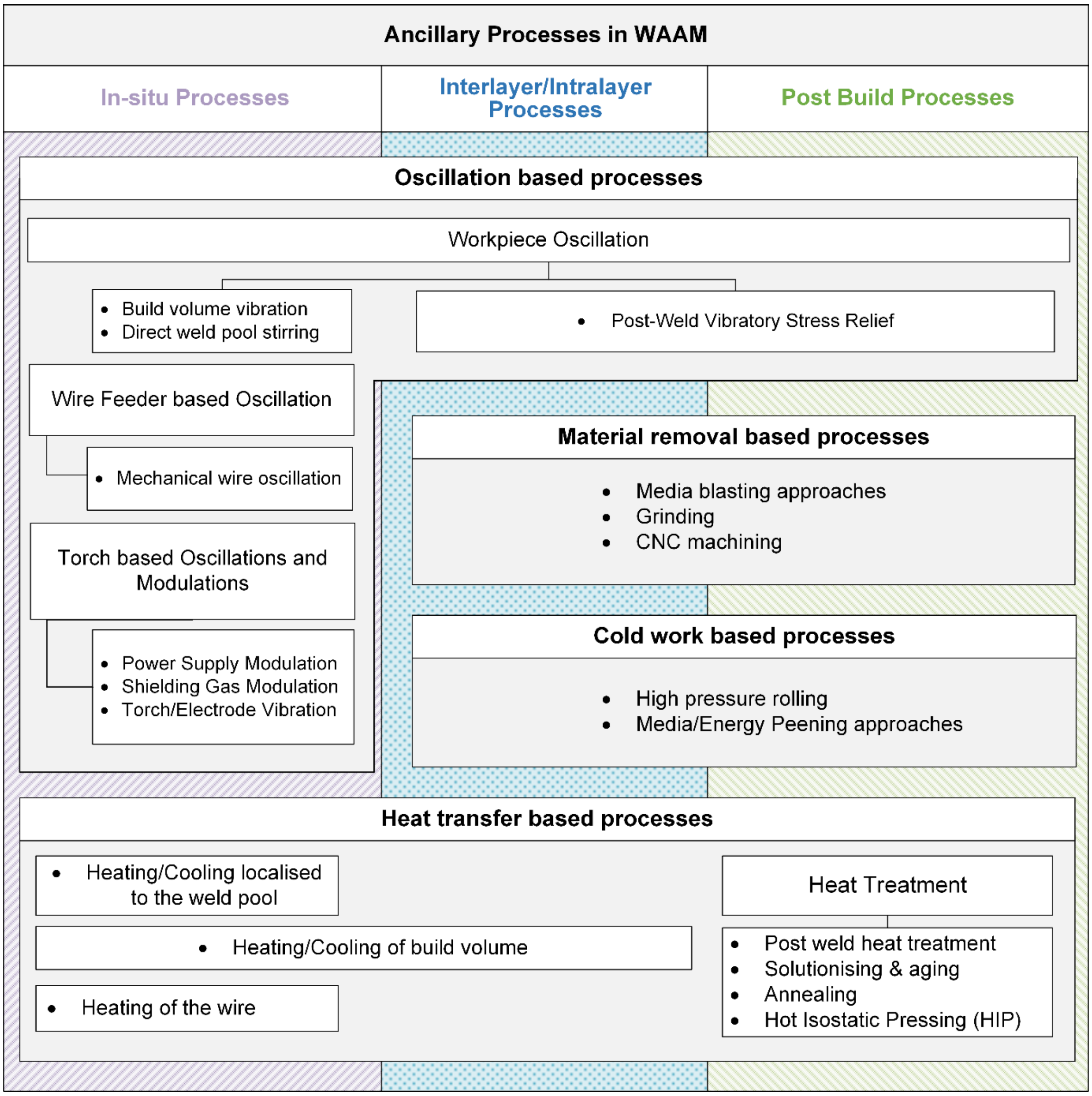

Figure 7 Classification of ancillary processes in WAAM

4.1. Oscillation-based processes

The following sections introduce the oscillation processes applied in-situ of WAAM deposition. These processes are categorised by torch, wire feeder, and workpiece as shown in figure 7. This is achieved as the oscillation based processes promote weld pool stirring which can lead to fragmentation of dendrites from the mushy zone at the rear of the weld pool and grain detachment from the partially melted grains at the weld pool sides [25]. As these particles are swept into the weld pool, they provide starting points for nucleation events, significantly decreasing the Gibbs free energy required to nucleate. Constitutional supercooling and a refined microstructure may also be encouraged due to increased mixing experienced within the weld pool [94]. A reduction in level of solute segregation may also occurs due to the greater grain boundary area, with associated benefits to the material properties and crack resistance during processing. Although residual stress is unchanged, the ability to withstand the stresses without distortion and cracking is improved.

4.1.1. Torch based oscillations

The torch based oscillations are classified as shown in Figure 8 and include sub-categories of power supply modulation, shielding gas modulation and oscillation of the weld torch and electrode. The following sections provide a literature review research conducted in these areas.

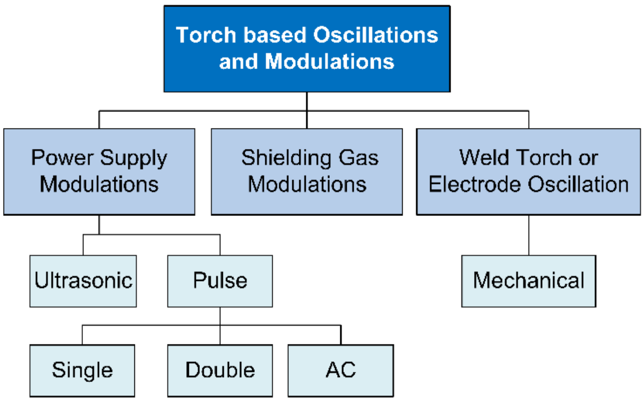

Figure 8 Classification of oscillation processes applied in-situ

4.1.1.1. *Power supply modulations*

Pulsing of the welding power supply current is a widely used technique and is a commonly available feature of modern welding power supplies. This process is able to decouple the metal transfer process from the baseplate heating process, as shown in Figure 9 [70]. The low current phase manages the arc stability and the high current phase, the droplet detachment. The frequency of pulse can excite the weld pool, changing the weld pool oscillations and subsequently the cooling rate.

In GMAW based WAAM of AZ31 magnesium alloy, a pulsed current was found to produce samples with refined equiaxed grains of higher ultimate tensile strength and yield strength than non-pulsed with similar to those of the forged AZ31 alloy. Maximum grain refinement was found at the resonant frequency which disturbed the geometrical accuracy. The weld pool has a natural oscillation frequency that depends on factors such as its size and shape, surface tension and viscosity. The natural frequency generally rises with a smaller weld pool size, ranging between approximately 10 and 200 Hz frequency [95]. In pulsed current welding of aluminium 7050 with non-heat treatable filler, grain size was small and precipitates in a uniformly distributed enough to enable direct aging of the material bypassing the need to apply prior solution heat treatment [96]. This was significant as solution and aging heat treatment is typically required to correct the grain growth, which is a cost and time intensive process.

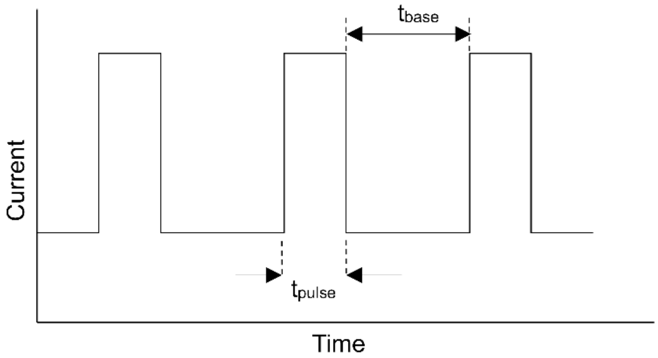

Figure 9 Schematic current waveform of single pulsed GMAW adapted from [70]

Double pulse waveforms may also be used where the pulse magnitude and frequency are time dependent as shown in Figure 10 [97]. This is reported to reduce porosity and refinement compared to standard pulse methods [97]. Wang, et al. [98] reported that this method allows control of cooling rate by changing current amplitude rather than heat input. Considerable temporal variation of fusion zone geometry, local cooling rates and solidification parameters were reported, and although apparently beneficial for material properties, due to the changing weld pool dimensions additional process planning measures may be required to efficiently achieve geometric properties in WAAM.

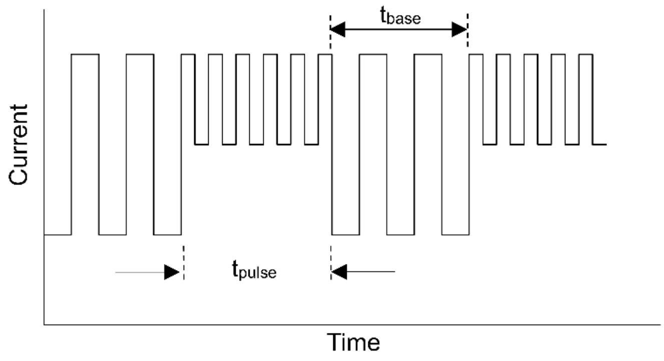

Figure 10 Schematic current waveform of double pulsed GMAW adapted from [97]

An alternating arc force can also be provided by alternating current (AC) or variable polarity (VP) methods, which are often preferred for removal of oxide layers in light metals. VP differs from AC in that the balance of the two polarities can be changed independently [99]. Wang, et al. [100] combined both variable polarity and double pulse methods in autogenous GTAW welding of aluminium alloy 2124. The amount of fine equiaxed grains increased significantly with a clear reduction of the coarse dendrite grains found with the conventional double pulsed approach, and more uniform distribution of the precipitations as shown in Figure 11.

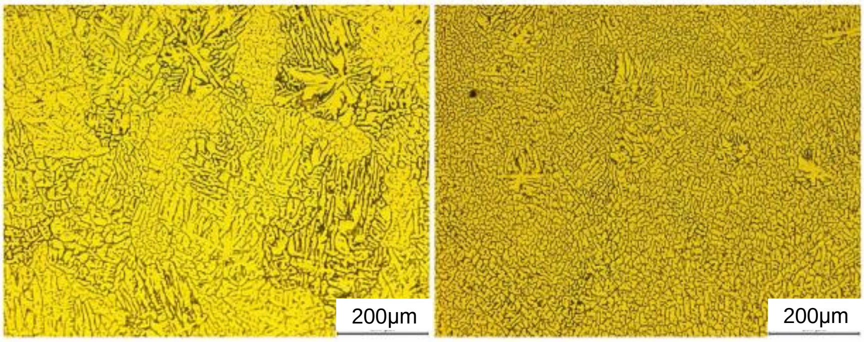

Figure 11 Microstructure of the weld zone a) conventional double pulse b) double pulse and variable polarity [100]

The electrical arc may also be excited via ultrasonic arc modulation. Hua, et al. [101] demonstrated this by superimposing an ultrasonic sinusoidal current of frequency 20 kHz to a DC GTAW welding power supply current waveform. Grain refinement through violent weld pool stirring in nickel filler metal FM-52M. This reduced the detrimental grain boundary length with more extensive branching of nickel dendrites which subsequently reduced the susceptibility to ductility dip cracking. In the same study, this technique was also found to be advantageous in reduction of the brittle Laves phase formation through dispersion of local niobium concentration to levels lower than the phase precipitation threshold.

4.1.1.2. *Shielding gas modulations*

This process involves the discrete periodic supply of two different shielding gases to the welding region in order to take advantage of the beneficial properties of each shielding gas [102]. This is in contrast to the mixed gas methods supplied from the same canister described in section 4.3. Wood [103] found that metal transfer modes could be transitioned noting spray transfer, buried arc globular transfer, and short circuiting within the molten weld puddle as the pulsing mechanism operated. The arc diameter reduced significantly the switching from argon to carbon dioxide indicating a vigorous stirring weld pool effect. Same penetration but with less CO_2. As a result of the pressure peaking present in alternating shielding gases, there is a momentarily greater arc force, thus permitting even faster travel speeds than the premixed helium addition while maintaining equivalent penetration. Ley, et al. [102] found for the same level of heat input to the workpiece, a lower shielding gas flow rate with reduced helium flow being used whilst also reducing distortion indicative of a cost effective and quality enhancing process. Chinakhov [104] found that weld bead droplet detachment could be regulated, and frequency increased to reduce workpiece heating time, penetration depth, and mean droplet size.

4.1.1.3. *Weld torch or electrode vibration*

Weld torch or electrode vibration also imparts oscillations to the weld pool to cause weld pool stirring. Biradar and Raman [105] applied 1.4mm amplitude mechanical oscillations to the welding torch across the direction of weld bead deposit, in GTAW welding of 6061 plates with 4043 filler material. This resulted in grain refinement and improved ductility. In vibration of the electrode in GTAW, higher arc pressure was with vibrations translated to the weld pool via the arc which improved the penetration compared to conventional GTAW [106]. Furthermore vibration of the weld torch in GMAW, the metal transfer was improved [107].

4.2. Wire feeder based oscillations

4.2.1. Mechanical oscillation of wire

Watanabe, et al. [108] reported improved mechanical properties for ultrasonic wire oscillation in GTAW of ferritic stainless steel with a columnar-to-equiaxed transition promoted at the weld centre-line and ductility improved significantly as shown in Figure 12. Wu and Kovacevic [109] found wire oscillation initiated more rapid and stable droplet transfer, improving the surface finish and increasing deposition rate. With this approach the minimum current could be reduced by 10-20% compared with pulsed-current welding, showing that ultrasonic wire oscillation can reduce heat input as well as directly impact the weld pool dynamics to affect grain refinement. Silwal and Santangelo [95] investigated the droplet dynamics as a result of wire oscillation for both cold and hot wire GTAW.

Cold Metal Transfer (CMT), an advanced GMAW process developed by Fronius GmbH [110] in the 1990's, combines wire and pulse oscillations to synchronise short circuit-controlled bead transfer. This process has been shown to be effective in joining of dissimilar materials. CMT pulse showed improved hardness in a Cu-Al alloy compared to standard pulse GMAW [111]. Sequeira Almeida and Williams [77] found the large columnar prior β grain were refined in Ti-6Al-4V. Further improvements were found for variable polarity CMT using Al-6Mg filler wire, where a columnar to equiaxed transition was made and ultimate tensile strength was maximised compared to pulse CMT [112]. Cong, et al. [57] found that the porosity was reduced in aluminium alloy (6.3%Cu) using CMT variable polarity pulse. Ola and Doern [113] by measuring the secondary dendrite arm spacing of CMT welds of Inconel 718 inferred that the cooling rate could be increased to levels expected of laser-based welding.

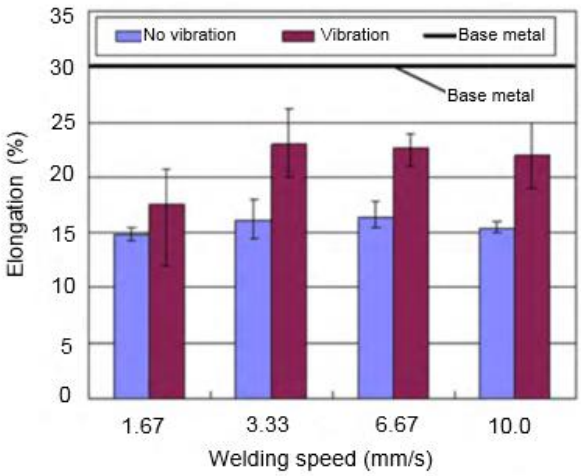

Figure 12 Fracture elongation of samples vs. travel speed, with and without ultrasonic wire oscillation adapted from [108]

4.3. Workpiece based oscillations

The workpiece based oscillations are classified in Figure 13 by power supply modulation, shielding gas modulation and oscillation of the weld torch and electrode. The following sections discuss the developments in these areas of research.

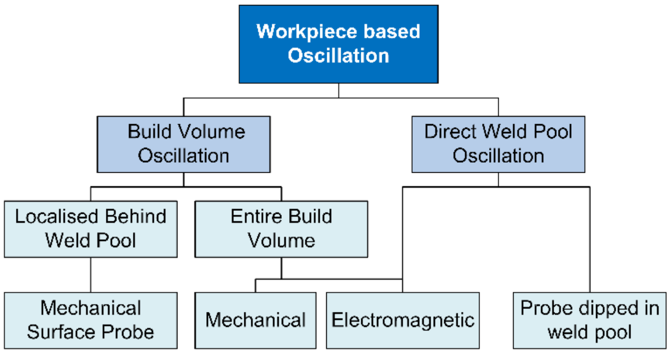

Figure 13 Classification of workpiece based oscillation processes applied in-situ

4.3.1. Build volume oscillation

Vibration of the build plate can be imparted by imposing a periodic external force with a typical approach shown in Figure 14 by Wen, et al. [114] in which a 2 kW transducer drives a tapered horn resonator and frame. Oscillation may also be generated by piezoelectric effect or by electromagnetic vibration. Yuan, et al. [115] reported that the mechanical approach to workpiece oscillation can be beneficial where the feed wire reduces the efficacy of arc-based approaches previously discussed. Thavamani, et al. [116] were able to refine the microstructure and hence reduce the hot cracking susceptibility of Inconel 718 and improve solute distribution through ultrasonic oscillation of the build plate for GTAW. Multiple researchers have investigated this for welding applications, however, investigation for WAAM has been limited perhaps due to the extensive energy requirement for oscillation of large parts.

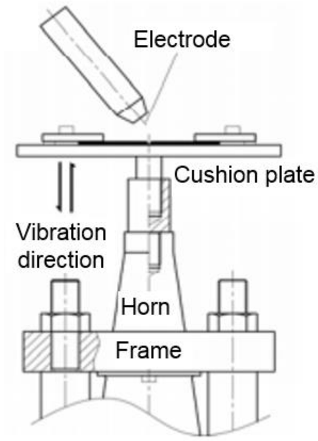

Figure 14 Schematic approach showing a typical approach to build plate oscillation [114]

4.3.2.Direct weld pool oscillation

Kou and Le [117] developed electromagnetic arc oscillation to directly modify the grain structure and solidification cracking tendency of welds. The magnetic field is produced parallel to the welding electrode and can be produced by single or multiple magnetic oscillators [118] and has been found to be most effective applied in the circular or transverse direction relative to the weld. The electromagnetic stirring produces a Lorentz force, which leads to rotation of the molten metal in the weld pool [94, 119]. Improvements to cracking resistance was found with this approach for nickel based filler metal FM-52 [120]. The effectiveness of mechanism is attributed to the ability to force columnar grains to reverse their orientation at regular intervals obstructing the progression of a crack propagation site as shown in Figure 15.

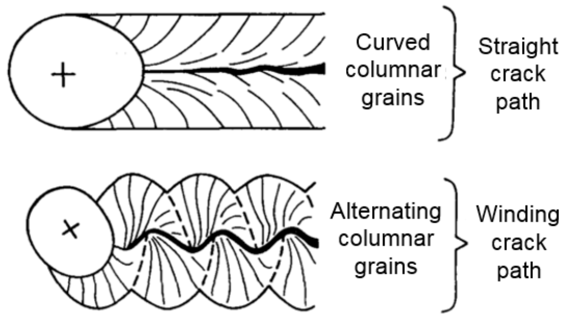

Figure 15 Schematic of crack path obstruction due to circular electromagnetic oscillation of the arc [117]

Yuan, et al. [118] reports that lower frequency operation is more effective for grain refinement as this allows enough time for the solidifying portion of the weld pool to be reheated and in the process provide more dendrite fragments. Mousavi, et al. [121] reported an intermediate frequency was most appropriate for grain refinement as at lower frequencies columnar grain growth is able to become established and at higher frequencies the ripples overlap and counteract each other. Matsuda, et al. [122] noted that the stronger the magnetic field the better the grain refinement, however this is counterbalanced by increased surface roughness and burn through, which may be unacceptable in production of WAAM parts. Pearce and Kerr [123] report that as well as constitutional supercooling, grain detachment may also increase nucleation rate.

Placement of a high temperature ultrasonic probe into the mushy zone of the weld pool also oscillates the weld pool directly, involves the. This has been found to induce significant levels of grain refinement for difficult-to-weld magnesium alloys AZ31 and AZ91 [115]. The improvement was attributed to the dendrite fragmentation within the mushy zone. This approach has the advantage of reducing the power requirement compared to build volume oscillation, however, due to the probe offset from the arc, it leaves an unrefined zone at the end of deposits as shown in Figure 16, which would have to be considered in WAAM path planning and potentially introducing zones of run off waste.

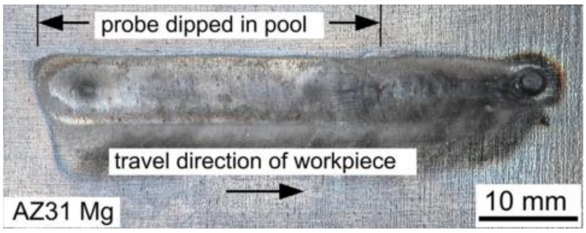

Figure 16 Weld bead of AZ31 Mg, showing grain refinement where ultrasonic probe is dipped into the weld pool and unrefined zone due to probe-torch offset [115]

4.4. Heat transfer-based processes

The following sections introduce the heat transfer-based processes that may be applied in-situ of deposition or inter/intralayer to change the total heat flux to the part during the WAAM process.

4.4.1. Cooling localised to the weld pool

Li, et al. [62] demonstrated in-situ cooling with a thermo-electric cooling device in WAAM of aluminium alloy 2325. It was shown that this was an effective way of maintaining stable heat dissipation characteristics without reducing the heat input and wire feed speed. For equivalent welding processing parameters this changed the weld bead geometry, increasing weld bead height meant that fewer deposition passes were required. It was shown that microstructure could be refined, and although an interpass dwell was required this was reduced by 60.9% compared to without in-situ cooling. This was used to establish a similar thermal boundary condition at the substrate and multilayer position compensating for the poorer heat dissipation at the multilayer level.

There have been multiple publications investigating in-situ cooling for welding. Wells and Lukens [124] investigated the effects of forced convective cooling behind the weld torch in autogenous GTAW welding of Ti-6Al-4V. They developed a cooling device in which helium gas, cooled by a surrounding water-cooled manifold is discharged through multiple holes in an impingement plate. The method was found to be effective in refining the microstructure of Ti-6Al-4V welds, by reducing time at transformation temperature and changing the shape of the weld pool. Van der Aa [125], in a similar approach, used the device applied solid CO_2 behind the weld pool. It was found that this approach could significantly reduce residual stress in single pass butt welding Ti-6Al-4V and SS316L. The distance from the cooling source to the weld pool was found to be critical to the efficacy of this process as the mechanism of stress reduction was dependent on influencing the weld pool shape and thermal field. To position the device close enough to the arc, whilst preventing turbulence, a physical shield was required, which offset the point of cooling to a minimum distance of 25mm. For this reason microstructural refinement was only found in materials of high thermal conductivity, as the critical portion of cooling is otherwise passed by the time that the cooling jet impinges. The buckling of thin sheets could be completely eliminated with this approach as shown in Figure 17 indicating a significant reduction in residual stress.

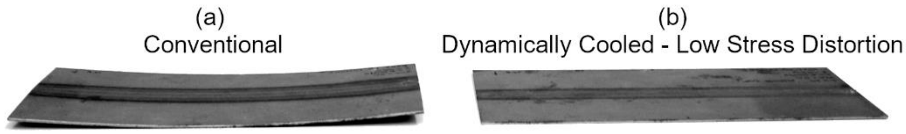

Figure 17 Distortion found in a) conventional butt welding and b) Dynamically Cooled – Low Stress Low Distortion of 1.5mm thick SS316L sheets [125]

Kala, et al. [126] found with cooling localised to the weld pool with liquid nitrogen that the process was also limited by severe arc disturbance. In this instance an argon curtain was used to protect the arc, however the extended distance from cooling jet to arc limited the efficacy of the process with regards to residual stress. Elimination of hot cracking and reduction in mechanical strain was possible in aluminium alloy 2024 with the use of a trailing heat sink of liquid nitrogen (LN_2) discharged from a spray nozzle, indicative of a reduction in residual stress [127].

4.4.2.Heating localised to the weld pool

Heating processes can occur in front or behind the weld pool at the centreline and also at a parallel offset. Bai, et al. [128] investigated the effects WAAM set up with symmetric induction coils mounted positioned ahead of and behind the weld torch as shown in Figure 18. Both positions were shown to reduce residual stresses by causing the distribution of heat input to become more homogeneous in both time and space. Norsk Titanium, a WAAM machine manufacturer and supplier to the aerospace industry, produces parts by plasma arc based WAAM [17]. They preheat the Ti-6Al-4V deposit with another plasma torch ahead of the bead deposition to increase deposition rate without incurring spatter and less consistent spray transfer. Qian et al. [129] investigated the effect of using a laser as an assisting heat source in plasma arc deposition. The shielding gas used in plasma arc deposition absorbed the laser energy and ionized gas molecules to improve the energy density of the plasma arc and arc diameter. This corresponded to improvements to minimum resolution of the process and part accuracy.

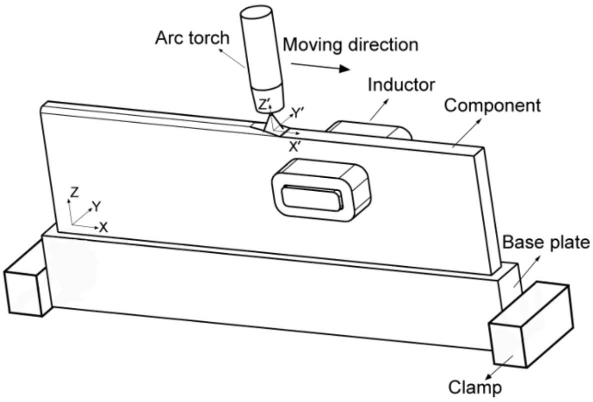

Figure 18 Induction pre-heating ahead of the weld pool [128].

4.4.3.Heating of the wire

Systems that provide separate heating of the wire, termed hot-wire welding, are widely available in the welding industry for GTAW. The primary benefit from a welding perspective is that the energy from the arc is enabled to melt a greater volume of wire compared to cold wire which subsequently increase deposition rates and productivity. Typically the wire feeder resistively heats the incoming wire feed [130]. Silwal and Santangelo [95] investigated hot-wire GTAW dynamics and found that for the same welding parameters the droplet detachment occurred at a higher velocity and frequency, and smaller bead width compared to cold wire approach. This resulted in a greater cooling rate and with greater weld pool mixing. This approach thus demonstrates potential for grain refinement, however, the microstructural differences for WAAM parts have not yet been investigated.

4.4.4.Heating/Cooling of Build Volume

Substrate platforms with integrated conformal cooling channels is a generalised heat transfer approach adopted for cooling of the build volume. Lu, et al. [53] embedded a pipe through a copper backing plate in GMAW-based WAAM. It was found continuous deposition was whilst maintaining geometric consistency was impossible without interpass cooling as shown in figure 19, whereas for the continuously cooled base plate continuous stable deposition was possible. However, Haselhuhn [86] found that WAAM implemented with water based substrate cooling negatively affected print quality by causing an increase in weld arc wander, more weld spatter, increased deposit minimum resolution and diminished surface finish. Furthermore, as this approach is reliant on conduction, the effectiveness of this approach in terms of the changes possible to implement regarding residual stress, microstructure and dimensional stability may be limited for components of larger size and lower thermal conductivities.

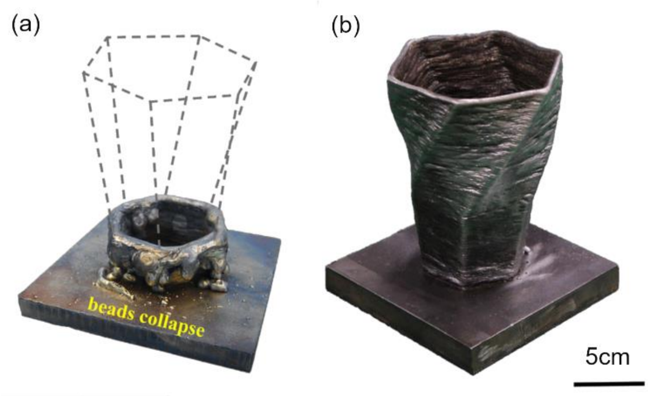

Figure 19 WAAM deposition (a) without (b) with water cooling of base of substrate [53]

Several types of cooling gases have been investigated for production of WAAM mild steel cylindrical pipe structures [131]. It was found that the cooling application was most effective in improving layer geometry and mechanical properties through grain refinement and homogenous hardness, in the position closest to the weld torch and cooling nitrogen with 5% H_2 was most effective. However, due possibility of nitrogen adsorption and deleterious effects the applicability to a wide range of materials is unclear. Additionally, the use of argon as a cooling gas would increase from 15L/min to 45l/min compared to with a non-cooling process. As argon gas consumption is a key cost driver in WAAM [132] this may reduce cost effectiveness of the process.

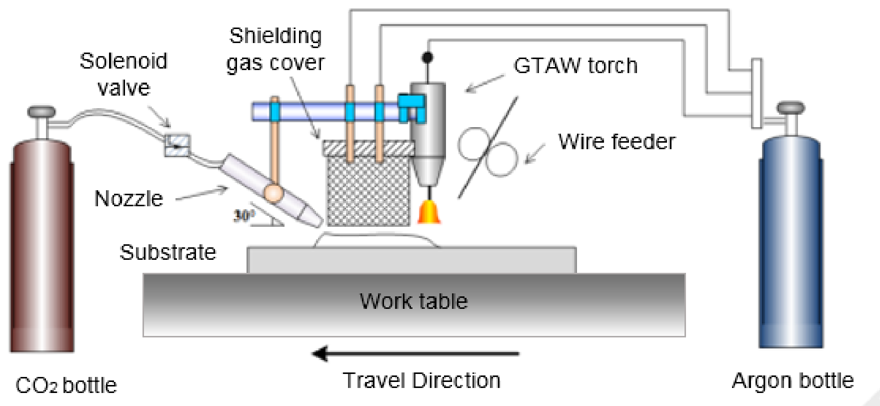

Figure 20 Active interpass cooling configuration of equipment adapted from [133]

Furthermore, Wu, et al. [133] investigated forced interpass cooling using compressed CO_2 gas in WAAM production of Ti-6Al-4V. This approach was explicitly selected to avoid arc disruption discussed in section 7.1. A schematic of the set up adopted is shown in Figure 20. This process was able to reduce the oxidation of the specimens produced as well as refined microstructure, improved hardness and enhanced strength. As the interpass temperature was carefully controlled, improvements to geometric repeatability and accuracy were achieved.

4.5. Cold-work based processes

High pressure interpass rolling, as shown in Figure 21, has been developed as a process for WAAM at Cranfield University in recent years. Applied vertically, this has been shown to effectively induce grain refinement, reduce anisotropy and residual stresses in aluminium alloy [134], steel [135], and titanium alloy [37] WAAM parts, as well as improve the geometric repeatability. A review by Derekar [136] conducts a review of the rolling process in WAAM, specifically for aluminium alloys. The process may be carried out immediately behind the welding torch. However, the temperature at which the rolling is carried out is important to the efficacy of the process. For example, due to greater thermal conductivity an application of an intralayer rolling process i.e immediately behind the welding torch achieved grain refinement in aluminium alloy 2024 [134]. However, negligible microstructural changes were found with this approach with Ti-6Al-4V, due to the need for lower rolling temperature, with an optimum interpass rolling temperature of 40°C found [37]. Despite the need to cool, McAndrew, et al. [137] recently demonstrated that productivity could be enhanced by effectively rolling of wider walls with use of an inverted profiled roller. Side rolling [138] was found to be significantly more effective than rolling vertically in terms of residual stress and distortion, however due to the need to support the thin wall against a block during the process, for consistent application process may be limited to linear thin wall applications to not require specialist tooling.

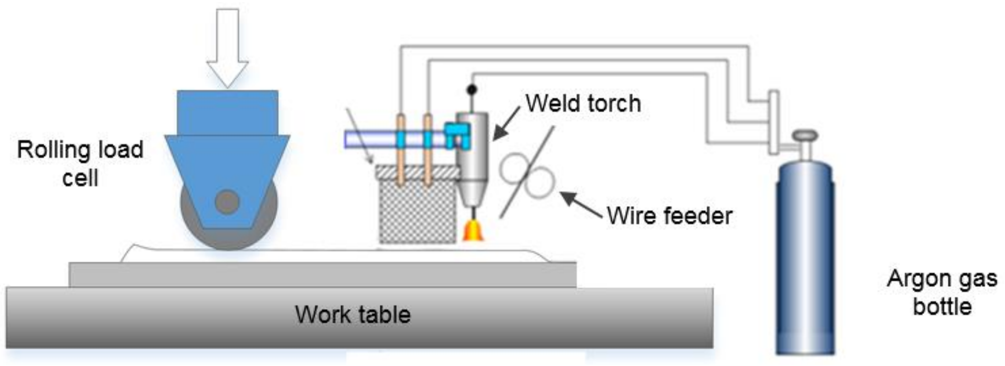

Figure 21 Schematic of trailing high pressure rolling in a GTAW based WAAM process adapted from [37]

Gefertec GmbH, refer to a rolling process in their patent [139], which is used for reshaping, surface roughness and productivity improvement. In contrast to other rolling methods cited, this takes advantage of the extended formability due the residual levels of heat in the build. Significant improvements in material properties were achieved with laser shock peening in WAAM [140]. Side rolling and machine hammer peening reduced porosity in aluminium alloys and an increase of surface hardness by 50-70% was achieved by peening and 20% increase was achieved by side rolling with 150kN load, as compared to as-deposited condition [141].

4.6. Material removal based processes

CNC machining on an interlayer basis is of benefit for part geometries with surfaces that are difficult to access post build, such as conformal cooling channels. These surfaces may be finished in process, as demonstrated with a WAAM system retrofit to a CNC machine [92]. Although intermittent CNC milling can be used to improve geometrical accuracy and surface finish [92] this approach reduces the material utilisation and manufacturing efficiency. As it is possible to maintain a stable deposition process through management of welding parameters by open loop [61] and closed loop control [142] of processing parameters, or an interpass dwell [69], this approach is no longer required.

5. Quality improving strategies for WAAM

The WAAM solidification characteristic, comprises of the thermal gradient and nucleation rate within the weld pool as shown in figure 22 and determines the primary performance measures for a specific location and the quality in-situ. As the thermal gradient affects the final performance measures of the layers beneath, until the reheat effect has no metallurgical impact, the and sets the thermal boundary conditions for the following layers of deposition, this aspect controls the heterogeneity that may be expected within the final as-built part and the quality. As outlined in section 3 and in figure 22, the primary process selections and the heat dissipation factor based on the geometry and infill strategy provide certain primary performance measures. However, the WAAM solidification characteristic obtained may be unsuitable for producing high quality WAAM parts efficiently. As shown in the diagram it is possible to introduce the ancillary processes classified and introduced within section 4, figure 7 of this paper to adjust the WAAM solidification characteristic and subsequently improve quality. In-situ processes, affect the solidification characteristic directly, whereas inter/intralayer processes can calibrate the primary performance measures to desired levels and affect the thermal boundary conditions for the following layer.

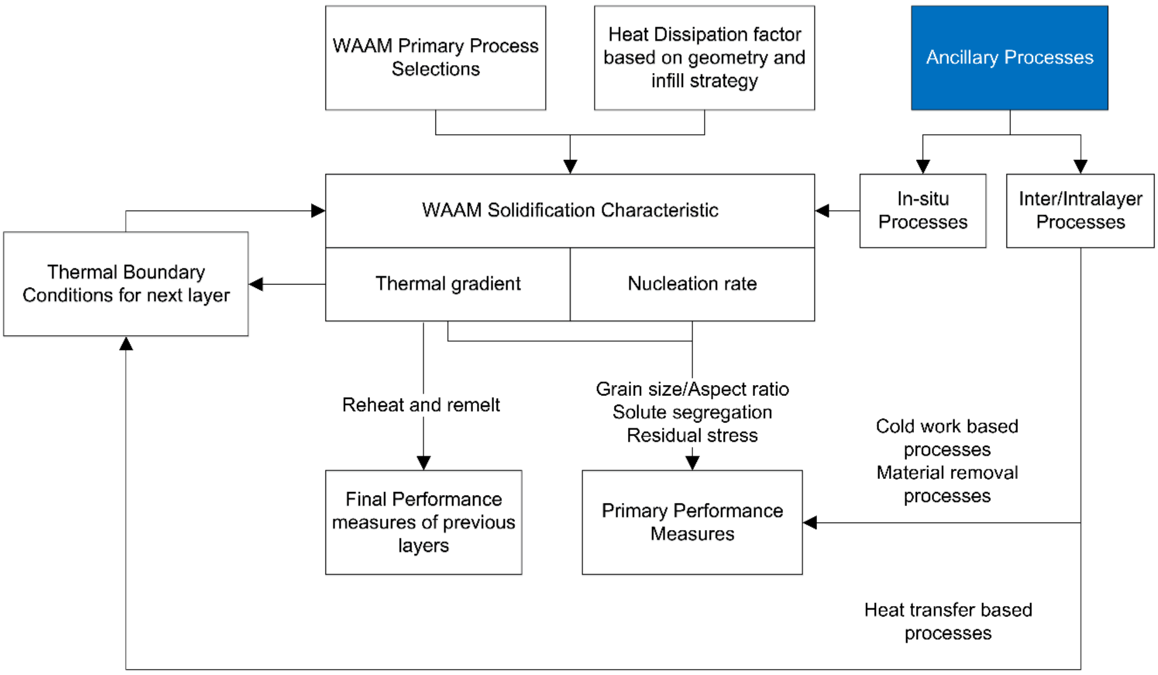

Figure 22 Flowchart primary and final performance measures development in WAAM

Increasing the nucleation rate within the weld pool through in-situ ancillary processes, provides a method of achieving significant disruption in average grain size and interruption the competitive columnar grain growth to develop equiaxed grain morphology. Processes which dynamically disrupt the shape of the weld pool, such as power supply and shield gas modulation, are particularly beneficial as shown in table 4 due to the ability to increase nucleation rate and also affect the thermal profile of the weld pool. This directly changes the heat input to the weld and hence more significantly affects the cooling rate and extent of constitutional supercooling compared to the other in-situ oscillation-based processes. However, processes, which directly affect the nucleation rate through weld pool stirring, have displayed greater capability in processing materials of high crack susceptibility than power supply modulation and shielding gas modulation.

Table 4 Strategies to alleviate materials processing challenges in WAAM

			Materials Processing Challenges Affected			
Applied:	Strategy	Mechanism	Phase changes	Grain size and solute segregation	Residual Stress	Thermal based Inhomogeneities throughout WAAM part
In-situ	Increase nucleation rate	Oscillation based processes or, Power supply or shield gas modulation	Indirectly	✓	× Management of residual stress is improved by grain refinement	× Effects may be improved by reduced micro-segregation
	Reduce WAAM total heat flux, impact of thermal cycling and set new boundary condition	Cooling local to weld pool or build volume Power supply or shield gas modulation	✓	✓	✓ Especially cooling localised to weld pool	✓
	Increase WAAM total heat flux, impact of thermal cycling and set new boundary condition	Heating local to weld pool or build volume Heating of wire	✓	×	✓	✓
Inter/ intralayer	Modify thermal cycling and new boundary condition	Heating/cooling, or Interlayer dwell, or Intralayer interval	✓	Indirectly	✓	✓
	Modify surface layer properties	Material removal	×	×	×	✓
	Modify sub-surface layer properties	Cold working	✓	✓	✓	✓

By implementing a cooling process localised to the weld pool or build volume, it may also be possible to also increase the nucleation rate, if surface nuclei are generated or constitutional supercooling is initiated. The localised approach in particular also allows steady state shape of the weld pool thermal profile to be modified with significant reduction to peak and amplitude values of residual stresses for conventional welding [125] than power supply and shield gas modulation. However, the transferability of these results to WAAM are yet to be established. An additional benefit of the cooling processes is that time at temperature is limited and grain growth can be hindered, leading to improved material properties and removal of interpass dwell [111]. Whilst build times are shown to have a small effect on the costs of production in WAAM generally [4], provides the ability to avoid one of the major limiting factors with regards to WAAM productivity which would otherwise have to be overcome with parallel working and more complex path planning strategies.

Furthermore, compared to a passive interlayer dwell or intra-pass interval, an in-situ cooling process may be preferential due to provision of more extensive control over microstructural and phase developments. This can be achieved as well with an inter-layer or intralayer heating or cooling, the WAAM build experiences different temperature characteristic compared to the aforementioned in-situ processes, whereby the heat flux changes work in series rather than in parallel to the weld torch. As shown in figure 22 this can, indirectly, affect the solidification characteristic by setting the thermal boundary conditions for the next layer.

The decision regarding the selection of heating or cooling processes, depends on the metallurgy of the material. A high interpass temperature build strategy allows the residual stress and time spent cooling to interpass temperature to be reduced. Implementing a constant interpass temperature may also allow the benefits of preheat, which is less effective due to the geometry in WAAM [143] to be captured. This is known to be beneficial in materials, where the high cooling rates during solidification in welding are detrimental to material properties. For example, in the production of precipitation strengthened stainless steels, there can be difficulties in developing the precipitates due to the rapid solidification [144]. To avoid martensitic transformation, mild steel AM parts require that the time at temperature between 800-500°C, to be greater than 30 seconds [145]. Even in martensitic steel, too high a cooling rate introduced retained austenite due to introduction of thermal stresses [146]. However, too high an interpass temperature can increase cross sectional weld bead geometry variations, known as humping [59]. Besides, control of the thermal profile can be used to affect post-solidification developments. Xu et al. [147] found that an operating temperature 600-850°C in SLM processing of Ti-6Al-4V, decomposed martensite to improve anisotropy and residual stress associated with the volume transformation. Based on this decision a strategy to limit heterogeneity due to thermal cycling and geometrical features is required. Cooling processes provide the ability to accelerate to the interpass temperature which may reduce the differences in thermal profile throughout the build. In addition, heating processes reduce the transition zone by accelerating to the pseudo-steady state temperature if the interpass temperature is high [59].

For heating of the build volume, the interlayer approach provides the opportunity to use of existing resource of the welding torch, however, at the expense of productivity. An intralayer interval, i.e. restarting at a location that has already cooled to the interpass temperature may be implemented without affecting productivity. However, it may not be feasible for small components where time cooling to interpass temperature is high compared to time depositing [12, 41, 69] and for components made from materials of high heat capacity and low thermal conductivity, such as Ti-6Al-4V. Furthermore, implementation is dependent on a comprehensive online knowledge of the heat distribution within the WAAM part to determine the position where to restart and build the next layer, which may hinder uptake until appropriate online-monitoring technology and path planning software is widely available.

Material removal processes are the only possible on an interlayer basis are the only possible way of accessing features which are enclosed by the end of the build. An opportunity provided by interlayer CNC machining is reduction in non-value adding time with the WAAM process by using the time assigned to cooling to the interpass temperature by machining in this period of time. However, limited understanding exists on the machinability of WAAM parts and the feasibility of machining at high temperatures, although if material softens this may enhance machinability. Other benefits that may be explored include the removal of oxides on the surface of the WAAM deposit. This may be achieved by interlayer CNC machining, however, alternative material removal processes such as ablation methods, sand or bead blasting, and CO_2 are also potentially feasible in addressing this problem.

Cold work based processes can effectively reduce inhomogeneity in material properties and impart quality improvements to the previous layer of deposit. By deforming the material the geometrical properties of the weld bead can be made more repeatable [148]. Positive internal stresses may be induced which can lead to work hardening and recrystallisation of grains which may be used to refine the grains and mechanical properties. Approaches can include high pressure rolling. As shown in table 4, with implementation of cold working based processes, it may be possible to implement many of the beneficial changes made possible in-situ. However, due to the need for a certain extent of cooling of the build before rolling is effective, this is incompatible with a high interpass temperature build strategy that is sometimes preferred for example in Ti-6Al-4V in order to minimise dwell periods and relieve residual stress throughout the build. As residual stress is effectively relieved in rolling, this may be acceptable, however, a significant amount of non-value adding time may be added, especially as the interpass rolling temperature may be well below the compulsory interpass temperature for build stability. This compounded by the need for rolling process on a layer by layer basis, with effects found to be less effective when applied in multiple of layers. Further processing issues involve the effective deployment of the roller for complex or bulk deposits.

Mechanical and energy based peening methods are also possible and may include use of electron, laser, ion, and fluid jet [149]. Well adopted methods in the welding industry include shot and hammer peening and according to Coules [150], needle ultrasonic, and laser shock peening have become more widespread in recent years. In the past, such peening processes were primarily related to surface treatments to improve fatigue life, however, as emphasised in the review paper by Sealy et al. [151], this is now an integral method for influencing properties throughout the part in hybrid AM, although the set-up of the process within a WAAM machine to achieve the required depth of impact requires further investigation.

6. Future Perspectives and Conclusions

With growing acceptance in the market for additively manufactured end products, the development of strategies and processes to overcome the materials processing limitations in WAAM are of prime importance. For this reason, to produce end-parts in challenging materials, enhancement of processing capability through integration of the ancillary processes identified and reviewed in this paper is envisioned. The ancillary processes have been classified by timing of application and mechanism. Strategies by which these processes may be applied to enhance quality of WAAM parts have been determined to provide guidance to ancillary process selection based on the material property improvements sought.

With market demand for high quality WAAM parts, it is expected ancillary processes will see greater adoption, and become advanced and diverse in future years. To date the most commonplace ancillary process implemented in WAAM involves the modulations of the heat input from the welding torch. There is evidence these processes becoming more advanced to meet the strenuous requirements of WAAM, with increasingly varied and advanced processes investigated in the published literature over the last 10 years. For example, standard pulse welding processes appears to be transitioning to advanced pulse and oscillation based methods such as cold metal transfer (CMT) [57, 112, 152] and variable polarity approaches [100, 112]. However, this process category cannot manage fully the wide ranging metallurgical requirements for producing WAAM parts of challenging materials. This paper has revealed the enormous capabilities of the full range of ancillary processes to enhance quality of WAAM parts. In selecting ancillary processes, there may be a range effective routes in terms of achieving the performance measures, as evidenced by the separate approaches by Norsk Titanium and Cranfield University for producing Ti-6Al-4V components. The ease of integration with existing WAAM equipment, adaptability of the process to the range of materials to be produced and the impact on the non-value added time will formulate key aspects of industrial adoption, as well as the efficacy of the process in terms quality enhancement itself.

As WAAM matures as a commercial manufacturing process, to provide a versatility, it will be important too that the ancillary processes selected are capable of enhancing quality in multiple materials. To achieve this, the ancillary processes will require adjustable settings to effectively develop different metallurgies on one machine. This is already possible in many of the processes, for example, the pulse heat input modulation, oscillation of build volume and rolling. However, heat transfer based processes investigated to date have had limited ability to adjust the cooling or heating capacity or timing of application. The widespread acceptance and uptake of CMT, indicates synergistically combining processes can be particularly powerful, however, synergic ancillary process combinations currently are primarily limited to include power supply modulation as one of the processes. Due to the exclusivity of the effects on material properties, material removal processes are likely comprise one such combination if enclosed finished features are to be manufactured.

Due to the array of potential processes and process combinations, advanced computation and mathematical tools, such as machine learning, decision science and process modelling, are required to develop resource-efficient process planning techniques. Development of novel process planning techniques to balance tool paths and infill patterns with primary process selections and the ancillary processes to minimise inhomogeneous material properties attributed to geometrical changes.

Technical advancements in processing capability imparted by in-situ and intralayer/interlayer, processes mean it may be possible to manipulate grain size and solidification mode throughout the part, providing a route to functionally graded materials in large scale parts. On-machine development of material properties, presents a great opportunity for reducing the overall post-processing time and cost for WAAM parts. Knowledge of on-machine development of material properties will also aid in feature addition or repair WAAM applications, where heat treatment is unfeasible. In summary, the future vision of this research area involves the emergence of highly capable WAAM machines that may combine manufacturing processes from a number of process categories to efficiently transform numerous raw materials into finished parts with minimal post processing.

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